Light thermal dark matter and its possible probes

[arXiv:2205.10149 [hep-ph]]

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LAPTh, Annecy
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in collaboration with
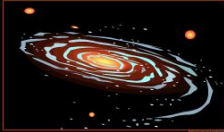
Tobias Binder | Shigeki Matsumoto | Yu Watanabe
Kavli IPMU, University of Tokyo, Japan
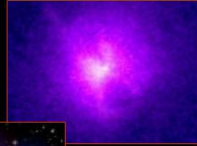
Evidence for Dark Matter

Rotation of galaxies

Velocities of galaxies in clusters

Velocities of stars in dwarf galaxies

Hot gas in galaxy clusters

Galaxy interactions

Collisions of galaxy clusters
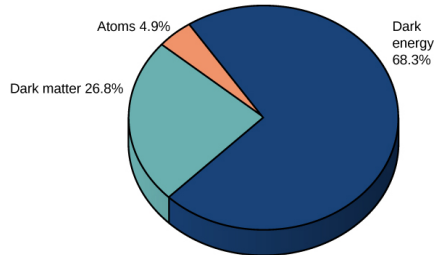
Gravitational lensing

Cold: moves much slower than c

Pressureless: gravitational attractive, clusters

Dark : no/weakly electromagnetic interaction

Collisionless: no/weakly self-interaction or interaction with baryons

**Abundance:** amount of dark matter today known

Atoms 4.9%

Dark matter 26.8%

Dark energy 68.3%

What is DM? What is its nature?

|		
~~Cold~~ →	How cold it is?	WDM
~~Pressureless~~ →	Cluster on all scales?	
~~Dark~~ (transparent) →	Non-gravitational interaction?	Milicharged DM
~~Collisionless~~ →	How small self-interaction	SIDM

Although still behaves
like CDM on large scales

Small scale behaviour: still weakly constrained
and small scale challenges

Missing Satellites

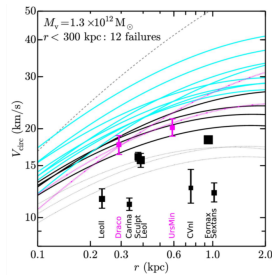Pawlowski/Bullock/Boylan-Kolchin
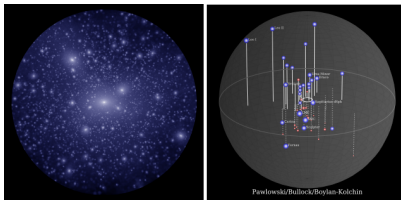
Discrepancy between the # of satellites
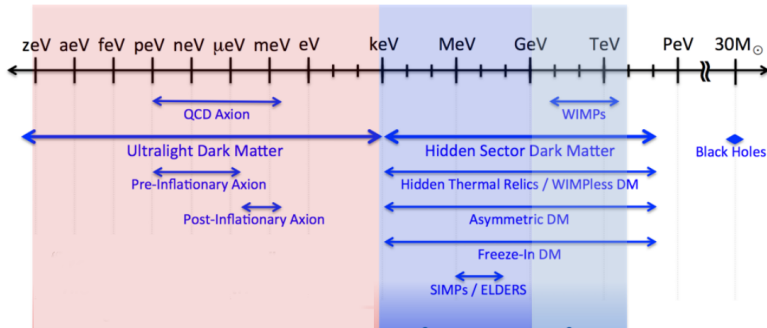predicted by ΛCDM
and the # observed satellites

Core-cusp problem
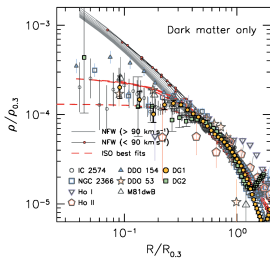
N-body simulations (CDM)
show cuspy density profiles
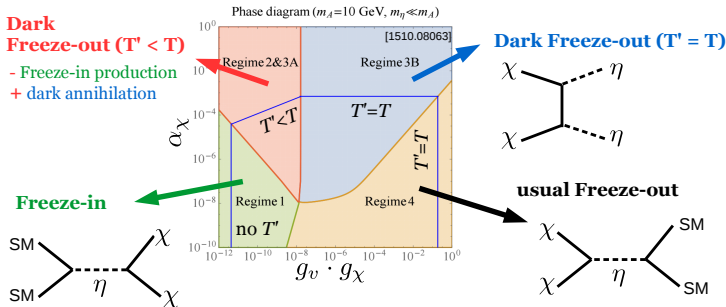(NFW), whereas observations
indicate a cored structure.

Too big to fail

Different thermal histories of DM

$$\mathcal{L} = \mathcal{L}_{SM} + \mathcal{L}_{HS} \left(\begin{array}{c} \chi \\ \chi \end{array} \right)^{\!\!\chi} \stackrel{g_\chi}{\cdots} \eta \ + \ \begin{array}{c} SM \\ SM \end{array} \stackrel{g_v}{\cdots} \eta \right)$$

Dark Freeze-out (T' < T)
- Freeze-in production
+ dark annihilation

Dark Freeze-out (T' = T)

Freeze-in

usual Freeze-out

Phase diagram (m_A=10 GeV, $m_\eta \ll m_A$)

[1510.08063]

Regime 2&3A   Regime 3B

T' < T   T' = T

T' = T

Regime 1
no T'

Regime 4

α_χ

$g_v \cdot g_\chi$

Chu, Hambye & Tytgat, 1112.0493
Bernal, Chu, García-Cely, Hambye & Zaldivar, 1510.08063

T': temperature of dark sector
T: temperature of visible sector

credit : Bryan Zaldivar

WIMP paradigm: $\sigma_{ann}(v/c) \approx 1$ pb $\Rightarrow \Omega_{DM} \approx 0.12$

Electroweak mediators $\Rightarrow$ Lee − Weinberg window

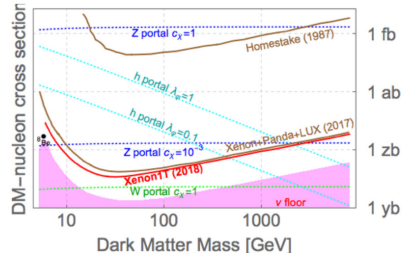$$\sigma(v/c) \propto \begin{cases} G^2_F \, m^2_{DM} \text{ for } m_{DM} \ll m_W \\ \\ 1/\, m^2_{DM} \quad \text{for } m_{DM} \gg m_W \end{cases}$$

$\Rightarrow$ few GeV $< m_{DM} <$ few TeV

It modeled decades of direct search experiment designs

WIMP miracle

But.....
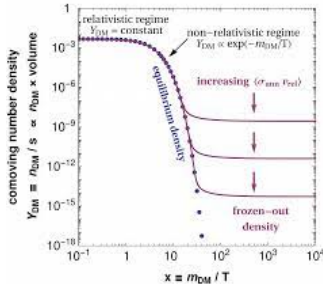
Maybe lighter dark sectors?

Freeze-out scenario with **light dark matter** requires a **light mediator** to explain the relic density, or dark matter is overproduced.

But.....
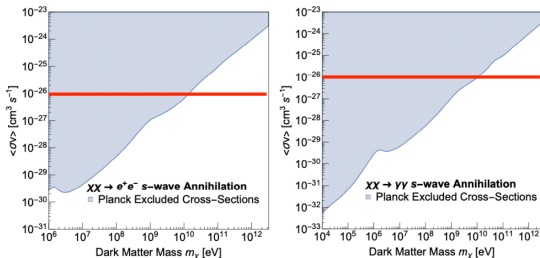
Liu et. al, 2016

- Light DM below 10 GeV is excluded by CMB if DM annihilation into SM is *s*-wave.
- The constraint is much weaker if other partial waves are dominant in the annihilation cross-section

Forbidden DM
Resonant DM *Katayose et. al, 2021*

Let's take an example....

New particles

scalar 1 : χ, Z_2 odd $\rightarrow$ **DM**
scalar 2 : ϕ', charge neutral

$$\mathcal{L} = \mathcal{L}_{SM} + \frac{1}{2}(\partial_\mu \chi)^2 - \frac{\mu_\chi^2}{2}\chi^2 - \frac{\lambda_{H\chi}}{2}|H|^2\chi^2 - \frac{\lambda_\chi}{4!}\chi^4$$
$$+ \frac{1}{2}(\partial_\mu \Phi)^2 - \frac{\mu_{\Phi\chi}}{2}\Phi^2\chi^2 - \frac{\lambda_{\Phi\chi}}{4}\Phi^2\chi^2 - V(\Phi, H),$$

$$V(\Phi, H) = \mu_{\Phi H}\Phi|H|^2 + \frac{\lambda_{\Phi H}}{2}\Phi^2|H|^2 + \mu_1^3\Phi + \frac{\mu_\Phi^2}{2}\Phi^2 + \frac{\mu_3}{3!}\Phi^3 + \frac{\lambda_\Phi}{4!}\Phi^4,$$

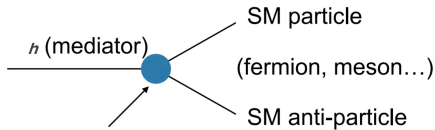## After the electroweak symmetry breaking
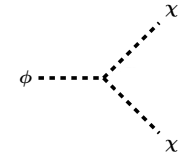
$H = (0, v_H + h')^T/\sqrt{2}$, $v_H \simeq 246\,\mathrm{GeV}$

$\Phi = v_\Phi + \phi'$, $v_\Phi = 0$

$$\begin{pmatrix} h \\ \phi \end{pmatrix} = \begin{pmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} h' \\ \phi' \end{pmatrix}$$

$$\mathcal{L}_{\text{int}} = -\frac{C_{h\chi\chi}}{2}h\chi^2 - \frac{C_{\phi\chi\chi}}{2}\phi\chi^2 - \frac{C_{hh\chi\chi}}{4}h^2\chi^2 - \frac{C_{\phi h\chi\chi}}{2}\phi h\chi^2 - \frac{C_{\phi\phi\chi\chi}}{4}\phi^2\chi^2 - \frac{\lambda_\chi}{4!}\chi^4$$

$$- \frac{s_\theta\phi + c_\theta h}{v_H}\sum_f m_f\bar{f}f + \left[\frac{s_\theta\phi + c_\theta h}{v_H} + \frac{(s_\theta\phi + c_\theta h)^2}{2v_H^2}\right]\left(2m_W^2 W_\mu^\dagger W^\mu + m_Z^2 Z_\mu Z^\mu\right)$$

$$- \frac{C_{hhh}}{3!}h^3 - \frac{C_{\phi hh}}{2}\phi h^2 - \frac{C_{\phi\phi h}}{2}\phi^2 h - \frac{C_{\phi\phi\phi}}{3!}\phi^3$$

$$- \frac{C_{hhhh}}{4!}h^4 - \frac{C_{\phi hhh}}{3!}\phi h^3 - \frac{C_{\phi\phi hh}}{4}\phi^2 h^2 - \frac{C_{\phi\phi\phi h}}{3!}\phi^3 h - \frac{C_{\phi\phi\phi\phi}}{4!}\phi^4 + \cdots$$

$$C_{h\chi\chi} = \lambda_{H\chi}v_H c_\theta - \mu_{\Phi\chi}s_\theta,$$
$$C_{\phi\chi\chi} = \lambda_{H\chi}v_H s_\theta + \mu_{\Phi\chi}c_\theta,$$
$$C_{hh\chi\chi} = \lambda_{H\chi}c_\theta^2 + \lambda_{\Phi\chi}s_\theta^2,$$
$$C_{\phi h\chi\chi} = \lambda_{H\chi}c_\theta s_\theta - \lambda_{\Phi\chi}s_\theta c_\theta,$$
$$C_{\phi\phi\chi\chi} = \lambda_{H\chi}s_\theta^2 + \lambda_{\Phi\chi}c_\theta^2.$$

h (mediator)

SM particle

(fermion, meson…)

SM anti-particle

suppressed by mixing angle

ϕ

χ

χ

not suppressed by mixing angle
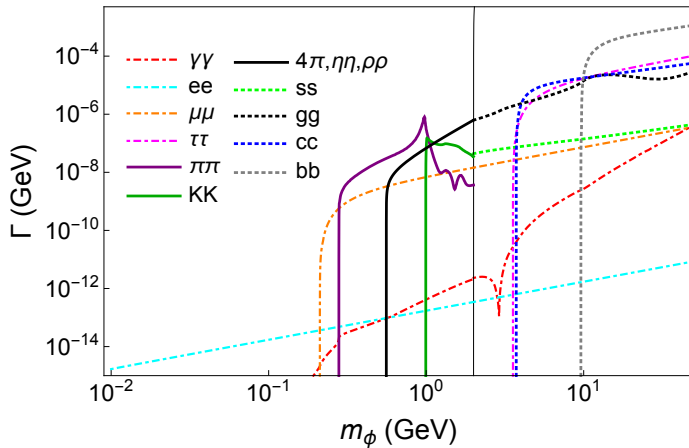
$$\Gamma\left(\phi \to \text{SMs}\right) = \sin^2\theta \ \Gamma(h_{\text{SM}} \to \text{SMs})\big|_{m_{h_{\text{SM}}}^2 \to m_\phi^2}$$

If $m_\phi > 2m_\chi$, mediator decays almost entirely into DM

we focus on

the **Resonant annihilation region**

$$\boxed{m_\phi \simeq 2m_\chi}$$

Mediator is a little heavier than twice of DM mass

- m_ϕ

- $v_R \equiv 2\left(\dfrac{m_\phi}{m_\chi} - 2\right)^{1/2}$

- $\gamma_\phi = \dfrac{1}{64\pi}\left(\dfrac{C_{\phi\chi\chi}}{m_\phi}\right)^2$

- σ_0

- $\sin\theta$

- $C_{h\chi\chi}$

- $C_{\phi\phi h}$

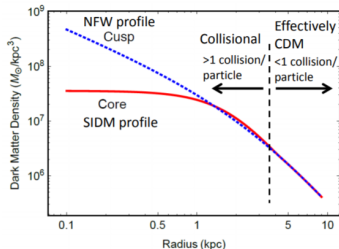- $C_{\phi\phi\phi}$

- $C_{\phi\phi\chi\chi}$

- $C_{\phi\phi\phi\phi}$

Why self-interaction?

A solution to small-scale structure problem

Direct detection of SIDM, S. Tulin

- Stronger self-scattering needed for (dwarf-sized) halos

  $\frac{\sigma_{SI}}{m_{DM}} \sim 0.5 - 10 \text{ cm}^2/\text{g}$ at dwarf scales of DM velocity $\sim 10 \text{ km/s}$

  O. D. Elbert et al. 2016, K. Bondarenko 2016,....

- Weaker self-scattering favoured by cluster merging/halo profiles etc

  $\frac{\sigma_{SI}}{m_{DM}} \sim 0.2 - 1 \text{ cm}^2/\text{g}$ at cluster scales of DM velocity $\sim 1000 \text{ km/s}$
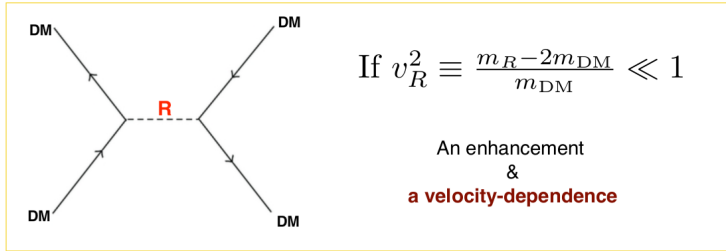
  O. D. Elbert et al. 2016, K. Bondarenko 2016,....

A velocity-dependence in DM self-scattering?

Possibilities : a light mediator

Spergel & Steinhardt 1999, Bringmann, et al. 2016

OR..

SIDM via a resonance [XC, C. Garcia-Cely, H. Murayama, 1810.04709]

If $v_R^2 \equiv \frac{m_R - 2m_{\rm DM}}{m_{\rm DM}} \ll 1$

An enhancement
&
a velocity-dependence

$$\sigma = \sigma_0 + \frac{4\pi S}{mE(v)} \cdot \frac{\Gamma(v)^2/4}{(E(v) - E(v_R))^2 + \Gamma(v)^2/4}$$

t/u - channel

$$\Gamma(v) = m_R \gamma v^{2L+1}$$
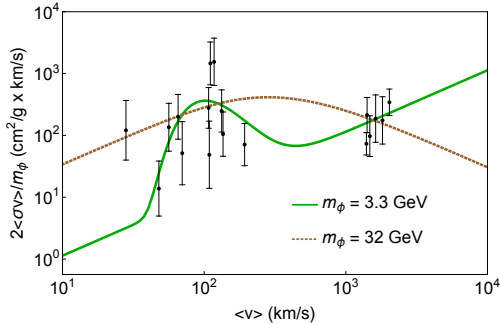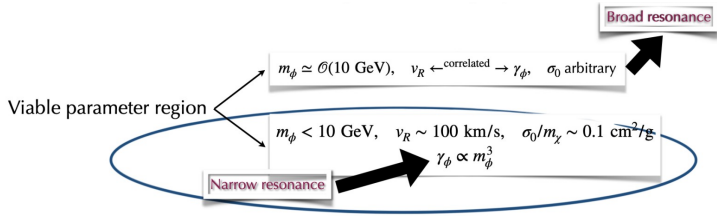
$$E(v) = \frac{1}{2}\frac{m}{2}v^2 \quad \text{and} \quad S = \frac{2J_R + 1}{(2J_{\rm DM} + 1)^2}$$

L — partial wave

γ — couplings

v_R — **near resonance**

Xiaoyong Chu, Humboldt Kolleg 2019

Viable parameter region

$m_\phi \simeq \mathcal{O}(10\ \text{GeV})$, $v_R \xleftarrow{\text{correlated}} \gamma_\phi$, σ_0 arbitrary → Broad resonance

$m_\phi < 10\ \text{GeV}$, $v_R \sim 100\ \text{km/s}$, $\sigma_0/m_\chi \sim 0.1\ \text{cm}^2/\text{g}$
$\gamma_\phi \propto m_\phi^3$ → Narrow resonance

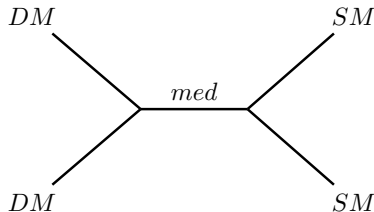$$\langle \sigma v(\chi\chi \to \chi\chi) \rangle_{v_0} \simeq \frac{2v_0}{\sqrt{\pi}}\sigma_0 + \frac{1}{2\pi m_\phi^6}\int_0^\infty dv\, \frac{v\, C_{\phi\chi\chi}^4\, f(v,v_0)}{(v^2 - v_R^2)^2 + 16\Gamma_\phi^2(s)/m_\phi^2}$$

$$\sigma_0 \equiv (\lambda_\chi - 2C_{\phi\chi\chi}^2/m_\phi^2 - 3C_{h\chi\chi}^2/m_h^2)^2/(32\pi m_\phi^2)$$

$(v_R, \sigma_0/m_\phi, \gamma_\phi, m_\phi)$: (110 km/s, 0.06 cm²/g, $10^{-7.9}$, 3.3 GeV)

(5035 km/s, 0, $10^{-1.1}$, 32 GeV)

- Dark matter annihilates into SM particles through s-channel resonance from ϕ mediation.

- Enhanced cross-section keeps the dark sector coupling down in order to match with the observed relic density

$$\sigma v \left(\chi\chi \to f_{\rm SM}\right) \simeq \frac{32 C_{\phi\chi\chi}^2}{m_\phi^5} \frac{[\Gamma\left(\phi \to f_{\rm SM}\right)]_{m_\phi^2 \to s}}{(v^2 - v_R^2)^2 + 16\Gamma_\phi^2(s)/m_\phi^2} \qquad \langle\sigma v \left(\chi\chi \to f_{\rm SM}\right)\rangle_{v_0} \simeq \int_0^\infty dv\, \sigma v \left(\chi\chi \to f_{\rm SM}\right) f(v, v_0)$$

$$\Gamma_\phi(s) \equiv [\Gamma\left(\phi \to \chi\chi\right) + \sum_{f_{\rm SM}} \Gamma\left(\phi \to f_{\rm SM}\right)]_{m_\phi^2 \to s} \qquad s \simeq m_\phi^2(1 + v^2/4)/(1 + v_R^2/8)^2$$

$$v_R^2 \equiv 4(m_\phi/m_\chi - 2), \gamma \equiv \Gamma_\phi^2(s)/m_\phi^2$$

For DM mass below 10 GeV, observed relic density fixes the mixing angle in the range

$$\boxed{10^{-6} \lesssim \sin\theta \lesssim 10^{-3}}$$

CMB puts a bound on electromagnetic energy injection into primordial plasma

An upper limit on $f_{\text{eff}}(m_\chi)\langle\sigma v\rangle_{v_{\text{DM}}}/m_\chi$

Slayter et al. 2016

efficiency

DM velocity
at recombination epoch

The velocity is estimated to be

$$v_{DM} \simeq 2 \times 10^{-7}(T_\gamma/1 \text{ eV})(1 \text{ GeV}/m_\chi)(10^{-4}/x_{kd})^{1/2}$$

$T_\gamma = 0.235 \text{ eV}$

$x_{kd} = T_{kd}/m_\chi$

In the early kinematical decoupling scenario, $T_{kd} \sim \mathcal{O}(T_{\text{freeze-out}})$

Since $v_{DM} \ll v_R$ ➡️ **only s-wave component contributes to annihilation at recombination**

But at freeze-out velocity is not so suppressed ➡️ so higher momenta also contribute to relic density

- We estimate the efficiency $f_{\text{eff}}(m_\chi)$ taking only leptonic final states into account

- PLANCK ➡ $f_{\text{eff}}(m_\chi)\,\langle\sigma v\rangle_{v_{\text{DM}}}/m_\chi \leq 4.1 \times 10^{-28}$ cm³/s/GeV at 95% C.L.

⬇

Mediator mass above ~ 4 GeV is excluded

But... 500 MeV $\leq m_\phi \leq 4$ GeV

No robust way to calculate fragmentation function for hadronic final states

ΔN_{eff}

- Adding new particles with mass close to the neutrino decoupling temperature $T_D \sim 2$ MeV to the dark sector affects expansion rate of the Universe at the recombination epoch
- CMB set a **lower limit** on the light mediator not to alter the effective # of relativistic d.o.f (ΔN_{eff})
- Assuming the instantaneous neutrino decoupling and no heating of the neutrinos from electrons and positrons

$$N_{\text{eff}} \simeq 3 \left\{ 1 + \frac{45}{11\pi^2 T_D^3} \left[s_\chi(T_D) + s_\phi(T_D) \right] \right\}^{-4/3}, \qquad s_i(T_D) = h_i(T_D) \frac{2\pi^2}{45} T_D^3,$$

$$h_i(T_D) = (15x_i^4)/(4\pi^4) \int_1^\infty dy\,(4y^2 - 1)\sqrt{y^2 - 1}/(e^{x_i y} - 1) \qquad x_i \equiv m_i/T_D$$
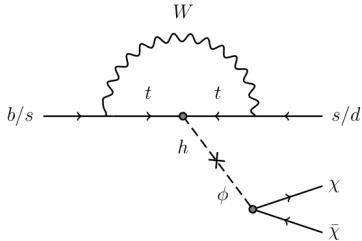
$$N_{\text{eff}} = 2.99 \pm 0.17$$

PLANCK excludes mediator mass below 11 MeV at 95% C.L

- Self-interaction
- Relic density
- CMB

• 1σ • 2σ
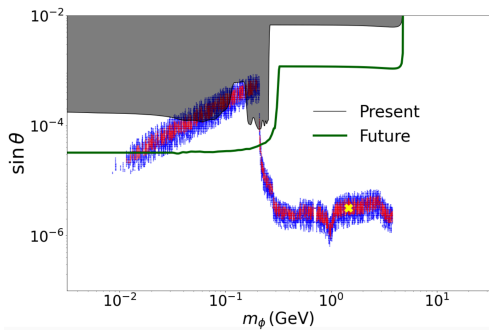
× Maximum likelihood
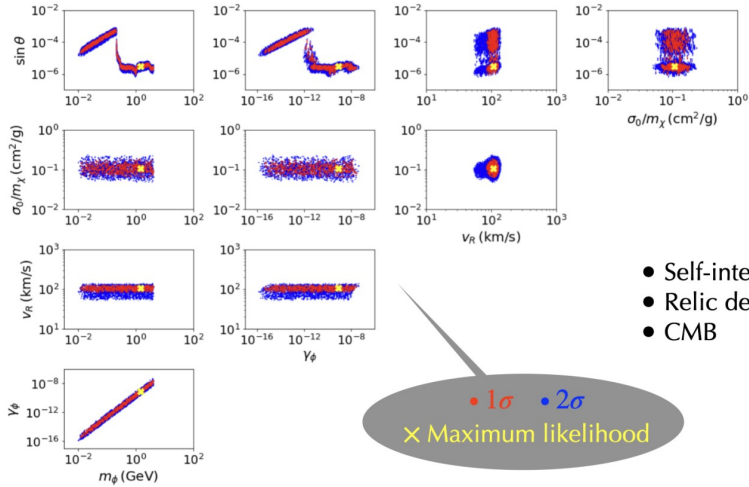
How to probe this model ???

the light mediator can be probed in the searches for
invisible decays of rare mesons

$$\Gamma(B^\pm \to K^\pm \phi) = \frac{|C_{sb}|^2 F_K^2(m_\phi)}{64\pi m_B^3} \left(\frac{m_B^2 - m_K^2}{m_b - m_s}\right)^2 \sqrt{(m_B^2 - m_K^2 - m_\phi^2)^2 - 4m_K^2 m_\phi^2}$$

$$\Gamma(K^\pm \to \pi^\pm \phi) = \frac{|C_{sd}|^2}{64\pi m_{K^\pm}^3} \left(\frac{m_{K^\pm}^2 - m_{\pi^\pm}^2}{m_s - m_d}\right)^2 \sqrt{(m_{K^\pm}^2 - m_{\pi^\pm}^2 - m_\phi^2)^2 - 4m_{\pi^\pm}^2 m_\phi^2}$$
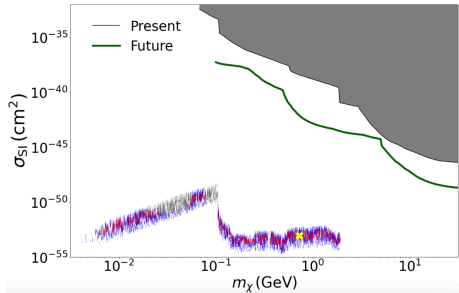
$$\Gamma(K_L \to \pi^0 \phi) = \frac{|C_{sd}|^2}{64\pi m_{K_L}^3} \left(\frac{m_{K_L}^2 - m_{\pi^0}^2}{m_s - m_d}\right)^2 \sqrt{(m_{K_L}^2 - m_{\pi^0}^2 - m_\phi^2)^2 - 4m_{\pi^0}^2 m_\phi^2}$$

- **Current limits** : Belle, BaBar, E949, NA62, and KOTO at 90% C.L

- **Future projections** : Belle II and KLEVER

$$\sigma_{\mathrm{SI}}(\chi N \to \chi N) = \frac{f_N^2 \, m_N^4}{4\pi v_H^2 (m_\chi + m_N)^2} \left(\sin\theta \, \frac{C_{\phi\chi\chi}}{m_\phi^2} + \cos\theta \, \frac{C_{h\chi\chi}}{m_h^2} \right)^2$$

- **Current limits** : CDEX, DarkSide-50 and XENON1T(M) at 90% C.L

- **Future projections** : NEWS-G, SuperCDMS, CYGNUS, and DARWIN

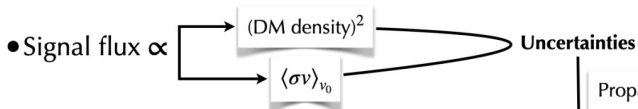Indirect detection can constrain DM annihilation into electromagnetically charged particles

For our analysis

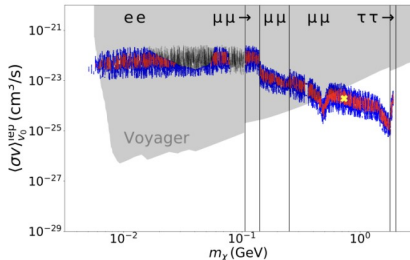$$v_R \sim 10^{-3} \sim v_{\mathrm{DM}} \text{ at present epoch}$$

DM annihilation cross-section at present epoch has the maximal contribution from the higher partial waves

Cosmic ray observations

- DM annihilation into leptons contributes to cosmic ray flux

- Signal flux $\propto$ → (DM density)^2 → **Uncertainties**
  → $\langle \sigma v \rangle_{v_0}$

Propagation B [*Boudaud et al. 2017, Kappl et al. 2015*]

Limits available from Voyager I, being the only cosmic ray detector located outside the heliosphere

$\rho_{DM}(r_\odot) = 0.25 \pm 0.11 \, \text{GeV/cm}^3$ [*Read et. al 2014*]
$v_0(r_\odot) \simeq 300 \, \text{km/s}$ [*Lacroix et. al 2020*]

- Annihilation considered only into lepton pairs
- Grey area excluded by Voyager I at 90% C.L.

Several parameter sets survive within
$250 \, \text{MeV} \leq m_\chi \leq 2 \, \text{GeV}$

gamma-ray flux from the dark matter annihilation at the galactic center
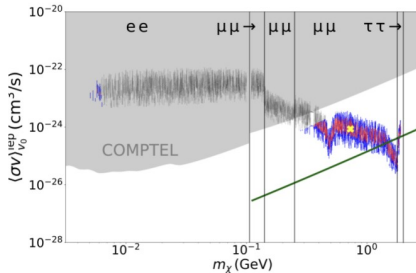
- $v_0 = 400$ km/s

$$\frac{d\Phi_\gamma}{dE_\gamma} \simeq \left[\frac{\langle \sigma v \rangle_{v_0}}{8\pi m_\chi^2} \sum_{f_{SM}} \mathrm{Br}\left(\chi\chi \to f_{SM}\right) \frac{dN_\gamma}{dE_\gamma}\bigg|_{f_{SM}} \right] \times \left[\int_{\Delta\Omega} d\Omega \int_{l.o.s} ds\, \rho_{DM}^2 \right]$$

J-factor

Produced photons typically have **MeV energies** ⇒ experimentally difficult to probe

COMPTEL (Current)

GECCO, COSI (Future)

- DM annihilation cross section into SM lepton pairs
- Grey area excluded by COMPTEL at 90% C.L.
- GECCO projection in green

Near future observation almost covers surviving parameter region for 250 MeV $\leq m_\chi \leq$ 2 GeV

- We consider a minimal thermal light DM model that resolves the core-cusp problem of the universe if the dark matter self-scattering occurs via the Breit-Wigner resonance caused by exchanging the mediator particle in the s-channel.

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- The model is compatible with self-interaction, relic density and CMB constraints in the dark matter mass range of $10\,\text{MeV} \leqslant m_\phi \leqslant 4\,\text{GeV}$.

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- A lighter dark matter region, $m_\chi \lesssim 300\,\text{MeV}$, is excluded by the indirect dark matter detection using cosmic-ray and gamma-ray observations, for the signal strength is boosted by the s-channel resonance.

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- The model is compatible with self-interaction, relic density and CMB constraints in the dark matter mass range of $10\,\text{MeV} \leqslant m_\phi \leqslant 4\,\text{GeV}$.

- There are strong constraints from collider searches due to the extensive search for rare K-meson decays. Moreover, future K-meson experiments can explore most of the parameter sets with $m_\phi \leqslant 100\,\text{MeV}$

- A lighter dark matter region, $m_\chi \lesssim 300\,\text{MeV}$, is excluded by the indirect dark matter detection using cosmic-ray and gamma-ray observations, for the signal strength is boosted by the s-channel resonance.

- Only the parameter sets with $300\,\text{MeV} \lesssim m_\chi \lesssim 2\,\text{GeV}$ avoid the severe constraints, although upcoming experiments in the near future is expected to probe this region.

BACKUP

Different signatures depending on the DM ↔ mediator mass relation
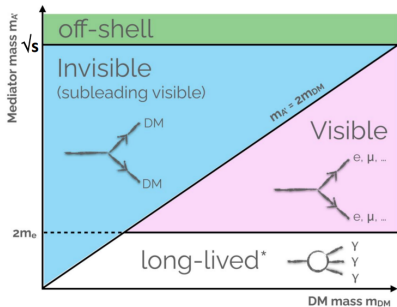
Probability of interaction of LDM detectors is negligible
- Search for mediators
- Search for missing energy signature
- Search for both

Additional benefits:

- Explanations of some astrophysics anomalies (PAMELA, AMS, FERMI, ...)

- Explanation of the $(g-2)_\mu$ effect ⟶

- Explanation (with additional hypotheses) of some flavour anomalies (LHCB, Belle, ...)

- Some light mediators (not interacting with quarks) could escape direct search exclusion limits

Early Kinetic Decoupling

- Small SM-mediator coupling reduces scattering rate between DM and SM particles in the thermal bath
- Suppressed scattering rate causes DM to kinetically decouple **much earlier** than the standard freeze-out case
- Phase space distribution differs from standard WIMP scenario. One needs to solve full Boltzmann Eq.
- Drastic drop in relic density around resonance than standard case $\Rightarrow$ smaller DM-SM coupling for EKD to maintain right relic

Binder et. al, 2017
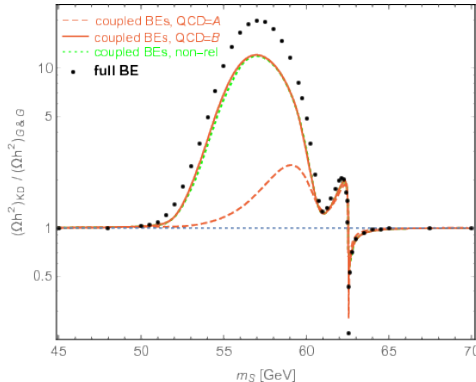
- The uncertainty on the "the relativistic degrees of freedom" leads to 10% ambiguity in the relic abundance when the freeze-out temperature is around the QCD phase transition

- The relic abundance calculated by taking all relevant scattering processes into account is the same as the one computed assuming no scattering between DM and SM particles at around 10 % level.

- 20 % of $\Omega_{\mathrm{DM}} h^2$ adopted as the standard deviation to take the ambiguities into account conservatively

We use **DRAKE** code to compute relic density with EKD

- Relic abundance including EKD effect becomes ~ 10 times smaller than that without the effect, leading to the favored mixing angle evaluated including the effect being ~ 6 times smaller than that without it.

For DM mass below 10 GeV, observed relic density fixes the mixing angle in the range

$$\boxed{10^{-6} \lesssim \sin\theta \lesssim 10^{-3}}$$

$$f_{\rm eff}(m_\chi) = \int_0^{m_\chi} dE \frac{E}{2m_\chi} \sum_{f_{\rm SM}} {\rm Br}(\chi\chi \to f_{\rm SM}) \left[2 f_{\rm eff}^{(e)}(E) \left.\frac{dN_e}{dE}\right|_{f_{\rm SM}} + f_{\rm eff}^{(\gamma)}(E) \left.\frac{dN_\gamma}{dE}\right|_{f_{\rm SM}} \right]$$

Efficiencies   Fragmentation functions
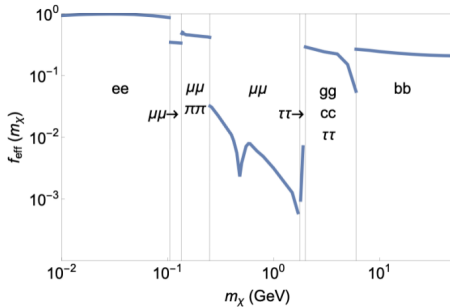
- $m_\phi \leq 2m_\mu$, $2m_\mu \leq m_\phi \leq 2m_{\pi'}$ and $2m_\pi \leq m_\phi \leq 500$ MeV   **HAZMA**

- 4 GeV $\leq m_\phi \leq 2m_b$, and $m_\phi \geq 2m_b$ **micrOMEGAs**

But... 500 MeV $\leq m_\phi \leq 4$ GeV

No robust way to calculate fragmentation function for hadronic final states

SIDM

II. SIDM halo model. Scattering between DM particles is more prevalent in the halo center where the DM density is largest. It is useful to divide the halo into two regions, separated by a characteristic radius r_1 where the average scattering rate per particle times the halo age (t_{age}) is equal to unity. Thus,

$$\text{rate} \times \text{time} \approx \frac{\langle \sigma v \rangle}{m} \rho(r_1) \, t_{age} \approx 1 \,, \quad (1)$$

where σ is the scattering cross section, m is the DM particle mass, v is the relative velocity between DM particles and $\langle ... \rangle$ denotes ensemble averaging. Since we do not assume σ to be constant in velocity, we find it more convenient to quote $\langle \sigma v \rangle / m$ rather than σ / m. We set $t_{age} = 5$ and 10 Gyr for clusters and galaxies, respectively. Although Eq. (1) is a dramatic simplification for time integration over the assembly history of a halo, we show by comparing with numerical simulations that it works remarkably well.
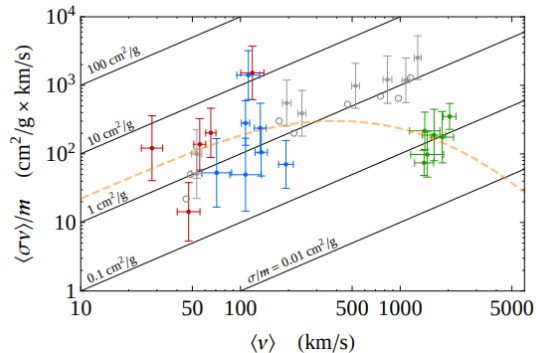

FIG. 1: Self-interaction cross section measured from astrophysical data, given as the velocity-weighted cross section per unit mass as a function of mean collision velocity. Data includes dwarfs (red), LSBs (blue) and clusters (green), as well as halos from SIDM N-body simulations with $\sigma/m = 1$ cm^2/g (gray). Diagonal lines are contours of constant σ/m and the dashed curve is the velocity-dependent cross section from our best-fit dark photon model